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Himalayan fermented beverages and their therapeutic properties with scientific validations: a comprehensive review

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Abstract

The Himalayan ethnoecology revolves around a balanced relationship between harsh mountain environment and the diverse lifestyles of its ethnic communities, where traditional knowledge on medicinal plants and fermented foods plays important role in their survival strategies. At high-altitudinal cold temperature and hypoxic condition, Himalayan tribal communities opt for easily digestible pre-digested foods rich in nutrients. Lack of suitable conditions for agriculture, the remoteness of the settlements, poor transportation systems, and limited availability of raw materials throw challenges to the agriculture and food production in the Himalayas which necessitate food preservation to extend shelf life. Thus, fermentation process is carried out to extend the shelf life of a food rather than just alcohol production. *Chhang*, *soor*, *tongba*, *jaanr*, *raksi*, *apong*, *yu*, *zutho*, *judima*, *chu*, *qingke*, *ara*, etc., are traditionally fermented beverages consumed in the Himalayan regions for relaxation which also offer health benefits. These ethnic beverages are often fortified with ethnomedicinal natural products native to the Himalayas which help inhabitants and tourists in coping with altitude-related stresses and acclimatizing to the region's climate. This review work begins with a background unfolding various altitudinal stresses on human health in Himalaya's perspective and continues with an investigation into the scientifically proven benefits of traditional fermented beverages. There is a pile of document that reports surveyed secondary data on identification of region specific starters and beverages, ethnobotanic preparations and ethnomedicinal claims of antioxidant, anti-inflammatory, antimicrobial, gastrointestinal-protective, rejuvenating and altitude-sickness healing properties. This review article identified the limited volume research on nutraceutical values of the Himalayan fermented beverages and described scientific validations of the ethnomedicinal claims through biochemical characterization, ethno-microbiology and metabolomics.

Keywords Himalayan ethnobiology, Altitude sickness, Fermented beverages, Medicinal properties, Food metabolomics

Introduction

Fermentation, a process conducted by microorganisms, transforms complex food components into desirable biochemical alterations that are suitable and easily digestible for human consumption with added nutritional and medicinal values. Fermented foods are widely consumed and play an important part of the diet for one third of the global population [1–3]. Traditional or indigenous fermented foods are examples of culinary preparations that were invented centuries ago and even found in written historical records [4]. Fermentation or preparation of alcoholic beverages is a five thousand year old practice in Indian subcontinent. One of the prehistoric examples of such beverage is *Soma*. According to ancient

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scriptures it is the oldest, most celebrated and mysterious alcoholic beverage of mainland India. The ancient Indian scripture *Rig-Veda* from 1700 BC mentioned *soma* several times, raising its status to the position of moon goddess [5]. Numerous scientists and scholars have documented various other ethnic beverages and their age-old preparations by glorifying traditional fermentation knowledge of the tribal people from India, Nepal, Tibet, etc. [5–8]. Among the historical archives, some documents as pioneer research on this topic have been found authored by Chopra et al. [9] (mentioning Himalayan ethnic beverages *raksi* and sub-Himalayan *haria* or *panchwai* as "Ethnic fermented beverage in India"); Paul [10] (on food and beverages of Sherpas); Ruchman [11] (role of millet-based liquor *raksi* in "Health and culture in Eastern Nepal"); Singh and Lal [12] (on "drinking practices in India with special reference to Punjab"); Holmberg [13] (on role of fermented beverages in "Tamang religious practice"); Ramble [14] (on role of Tibetan alcoholic beverages including *raksi* in "funeral ceremonies in a Bhotiya village"); Parker [15] (on role of fermented beverages in "culture of entrepreneurship among the Thakali of Nepal"); Paliwal and Badoni [16] (on role of finger-millet/*mandwa* and barley based alcoholic beverages like *chhang*, *jann*, *sur*, *ghenti* and *pakhoi* and starter *balma* in "ethnobotany of the hill tribes of Uttarkashi"); Bhattacharya et al. [17] (on role of staple food rice and rice based beverage *chhang* in migrant Tamang community in sub-Himalayan West Bengal) etc. To date, more than 350 types of indigenous fermented beverages have been reported in India including a lion share from the Himalayan region that are associated to Indian, Tibetan and Nepalese traditional knowledge system [5]. These beverages are generally region-specific, homemade, non-commercial and often brewed informally using simple techniques and equipment at the local or family level [5, 18, 19]. These beverages are prepared by cooking available cereal grains and other region-specific raw materials followed by fermentation using community-specific starters [19]. These traditional fermented beverages signify cultural importance in events and social activities.

Himalaya's ethnobiology stands upon people belonging to different ethnicities, their ways of life and their traditional knowledge on food fermentation and application of medicinal natural products. Availability of raw materials and production of food are influenced by factors such as altitude, weather conditions, soil quality, and other ecological aspects of a region. Altitude also influences human nutrition, food habits and other activities which diverges people living at high-altitude regions like the Himalayas from the rest of the world on the basis of food requirements and dietary preferences [20–22]. Arrangement of important functional foods throughout year is very difficult in the hills due to the lack of suitable conditions for agriculture, the remoteness of the settlements, poor transportation systems, and limited availability of raw materials. So, preservation of food is required to increase the shelf-life of processed or harvested food materials [21]. Consequently, large-scale food preservation is a problem where indigenous preservation techniques such as probiotic or lactic acid fermentation are employed to protect the available food from pathogens. Moreover, because of high-altitude, cold temperature induced stress and hypoxic condition, the tribal people prefer to consume pre-digested food which is not only rich in nutritional value but also easy to digest [9, 23–25]. Thus, these factors collectively influence fermentation process to extend shelf life of the food rather than just alcohol production from it.

The Indian Himalayan region has been recorded for around 250 varieties of ethnic fermented foods and beverages as products of Indo-Tibetan traditional knowledge system. Chopra et al. [9] pioneered research on documentation of alcoholic beverages in British India and reported various traditional alcoholic beverages from different provinces of India "with special reference to the conditions which determine their consumption in these areas". During discussing on the alcohols of Himalayas, they mentioned home-brewing of country beers such as *sur*, *lugri* and *chhang* was allowed under licence in certain areas within the Himalayan region. Later, these drinks became popular in the hilly terrain of the western Himalayas extending from Kashmir in the north to Lahaul, Spiti and Kangra of The Punjab province (now in Himachal Pradesh state) in south [9]. Moreover, the low price of molasses, due to the development of the sugar industry, and cheapness of rice influenced fermentation and illegal distillation. Chopra et al. [9] criticized "Nepalese tea garden coolies" by referring them as "well versed in this art" probably due to their traditional expertise in distilled *raksi* preparation. Ethnic beverages such as *zu*, *madh*, and *lao-pani* were also popular among aboriginal hill tribes [9]. Consumption of these local beers also extended along the border of the Himalayas right up to the Shan States in Burma [9]. Further east, *marua* was consumed in Arunachal and the neighboring hills while *zu* was popular among the Nagas [9].

Medicinal plants and traditional foods are referred as important elements of the ethnoecology by the people living in the mountainous regions of Himalayas. Seven traditional knowledge systems, including Ayurveda, Siddha, Yoga (Indian origin), Unani (Greek origin), Amichi (Tibetan origin) are recognized in India among which Ayurveda (in regions Uttarakhand, Himachal Pradesh, and northern Uttar Pradesh etc.) and Amichi (in Ladakh, Lahul-Spiti, Darjeeling Himalayas) are mostly practiced

in Himalayan region. Moreover, Himalayan traditional beverage *tongba* has Tibetan origin developed by Limboo ethnic community of Eastern Nepal [26]. Beverages like *chhang* and *raksi* also originated from unspecified locations within the Himalayan region of Nepal, Tibet and India. Sharma et al. [27] described influence of Nepalese traditional knowledge system in overall Himalayan food culture and ethnoecology. Therefore, influence of Tibetan and Nepalese traditional knowledge in Indian Himalayan region is very deep-rooted. The acquisition of ethnomedicinal knowledge can be determined from the production of local fermented beverages and food products in various settlements of the Himalayas. The consumption of different food products and beverages are directly related to customs, culture, and the traditions of the place that have been received over the years from their ancestors [8]. The beverages of various tribal communities were studied which revealed similarities in their production processes. However, the use of medicinal plants in starters varied based on their availability in specific regions, as detailed in the section on starters below. Several ethnic foods and beverages and ethno-medicines enriched with natural products indigenous to the Himalayas also help inhabitants and tourists to sustain the altitudinal stresses, recover from various high-altitude sicknesses and get acclimatized with the climate which remains frigid throughout the year [21]. The Himalayan region spans from west to east comprising one union territory (UT of Jammu and Kashmir) and twelve states of India (Ladakh, Himachal Pradesh, Uttarakhand, Darjeeling and Kalimpong districts of West Bengal, Sikkim, Dima Hasao or North Cachar Hills and Karbi Anglong districts of Assam, Meghalaya, Arunachal Pradesh, Nagaland, Mizoram, Manipur, Tripura); Nepal; Bhutan; and Himalayan regions of Tibet where traditionally fermented alcoholic beverages are consumed. Indigenous people of this region prepare their own starter cultures from region specific natural products that source microbes in the fermentation and additional medicinal properties to the brews. The satellite map of this region has been represented in Fig. 1. The well-known fermented drinks which are served in Himalayas include *sura*, *chhang*, *tongba*, *jaanr*, *raksi*, *apong*, *yu*, *zutho*, *judima*, *chu*, *qingke*, *ara* and much more. These drinks are served to celebrate special occasions emphasizing happiness and sharing. Moreover, these beverages offer functional properties that contribute to enhancing nutritional value, preserving

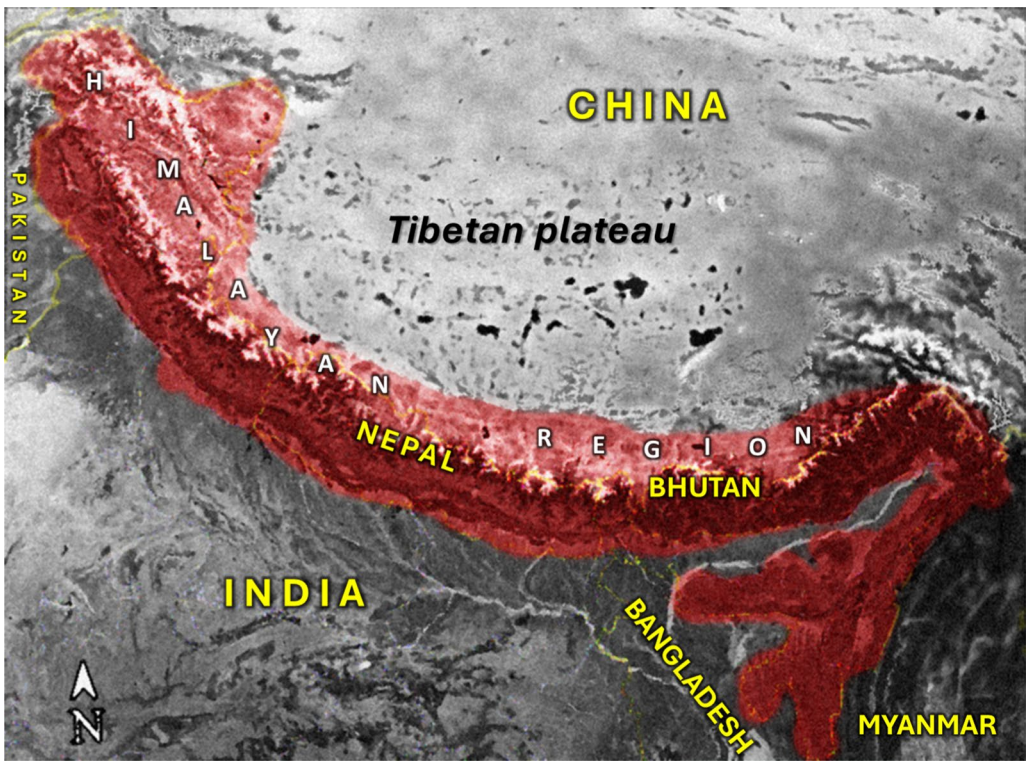

Fig. 1 Satellite map (artistic illustration) of the Himalayas including Tibetan Himalaya, higher and lesser Himalayas and sub-Himalayan high altitude regions which highlights (in red) the study area of this research i.e., the Himalayas and sub-Himalayan regions of India (twelve states and UT of Jammu and Kashmir), Nepal, Bhutan and parts of Southern-Tibet

perishable items, promoting probiotic properties, and improving mineral bioavailability [7].

Not long ago, researchers around India and the subcontinent explored both preparation techniques and ethnomedicinal values associated to traditional alcoholic beverages of the Himalayas and have initiated ethnobotanical field surveys to document the medicinal claims. Just like the preparation technique, the purpose of serving and way of serving of each and every beverage is unique. Some are taken for relaxation or intoxication (alcoholic drinks) while some confer health benefits by providing warmth and protection against cold stress induced disorders, major requirements in the high-altitude remote areas of the Himalayas. There are also few reports on investigation based on biochemical characterization, in vitro, in vivo and in silico bioactivity experiments, metabolomics and food-microbiological approaches to validate the claims and find out possible nutraceutical values of the beverages. All previous survey, laboratory experiments and meta-analysis scientifically validated therapeutic properties of these beverages—mainly antioxidant, anti-inflammatory, antimicrobial, anti-diarrheal (and other gastrointestinal-protective) and rejuvenating properties [5, 7, 8]. While these natural therapeutics are also claimed for various high-altitude sickness healing properties that are still underexplored scientifically [21, 22, 26, 28]. However, there is a serious lack of studies on the healing properties of high-altitude beverages, particularly from a Himalayan perspective, which demands the compilation, review, and meta-analysis of both recent articles and old pioneer research documents. This review will assist scientists and researchers in conceptualizing their studies and designing future experiments on Himalayan traditional fermented beverages.

Methodology of review

This review provides a thorough examination of Himalayan fermented beverages and their medicinal properties, highlighting significant research gaps and the potential avenues for future inquiry. The information sources or study materials were gathered from reputable academic research databases and search engines such as: BMC, SpringerLink, Digital Himalaya, Google Scholar, PubMed, ResearchGate, Scopus, ScienceDirect, Research Communities by Springer Nature, etc. Additionally, resources were also collected from government agencies, university repositories of theses and dissertations, national and international newspapers and magazines. The scope of this review was extensive, covering a wide range of publications (total 123) from 1942 to 2024 which allowed both historical and contemporary insights. Inclusion criteria encompassed the limited but important research papers published in peer-reviewed journals, proceedings and books, specifically focusing on biochemical and microbial characteristics of Himalayan fermented beverages and their therapeutic properties scientifically validated using state-of-the-art techniques. Studies not available in English language were excluded from consideration at this level for worldwide perspective. The keywords/search terms included 'Himalayas', 'Himalayan ethnic foods', 'Himalayan fermented beverages', 'survey', 'marcha', 'chhyang/chhang', 'raksi', 'jaand', 'nigar', 'guras' 'ethnic drinks of Indian Himalayan region/Nepal/Bhutan/Tibet', 'bioactive compounds', 'medicinal properties', 'GC–MS analysis/ metabolomics', 'ethnomicrobiology', 'high-altitude sicknesses', 'brewing', etc. To provide pictorial demonstrations for the review, maps of study area—Himalayan region—were drawn digitally. Maps and illustrations were made using software apps SketchBook and Microsoft PowerPoint. Photographs provided as figures were taken during survey and successive research works.

Study area

Traditional fermented beverages producing high altitude regions within the Himalayas were considered as the study area (Fig. 1) for this review which comprise different elevation zones of Himalayan region, such as Tibetan Himalaya, higher and lesser Himalayas and High altitude regions of sub-Himalayan region. These regions are inhabited by a moderate number of tribal populations of different ethnicities, mainly concentrated in the remote areas, who bear traditional knowledge of medicinal plants, ethnomedicinal preparations, food preservation, fermented food and beverages (both alcoholic and non-alcoholic), lifestyle and various other aspects. Some of the important Himalayan ethnic communities are: Sherpa, Gurung, Tamang, Rai, Limbu, Bhutia, Lepcha, etc. (from Nepal, Darjeeling hills, Sikkim, and parts of Tibet); Newar, Thakali, Khasa, Mustangi, Chepang, Jirel, Sunwar, Yakha, etc. (from Nepal); Dolpo, Manangba, Baragaonli, Nubri, Tharu, Magar, Pahari, etc. (from Nepal and North India); Tibetan and Khampa (from Tibet and parts of Nepal and India); Bhotiya (from Uttarakhand and parts of Nepal and Tibet); Kinnauri and Lahuli (from Himachal Pradesh); Ladakhi, Changpa, Drokpa, Brokpa, etc. (in Ladakh); Gujjar and Bakarwal (from Jammu and Kashmir), Kumaoni and Garhwali (from Uttarakhand), Sikkimese (found in Sikkim), Bhutanese communities like Lhokpu, Dzongkha, Drukpa, Sharchop, Bokar and others; Adi, Nyishi, Mishmi, Wancho, Nocte, Tangsa, Monpa, Sherdukpen, Apatani, Singpho, etc. (from Arunachal Pradesh); Angami, Ao, Chakhesang, Chang, Lotha, Phom, Pochury, Rengma, Sangtam, Sumi (Sema), Yimchunger, Zeliang (from Nagaland); Mizo (Lushai), Hmar, Mara, Chakma, etc. (from Mizoram); Tangkhul,

Mao, Maram, Poumai, Zeme, Liangmai, Anal, Chiru, Monsang (from Manipur); Bodo, Mishing, Dimasa, etc. (from Assam) (https://censusindia.gov.in/census.website/). These tribes have expertise to prepare medicinal formulations, fermented foods and alcoholic drinks with the indigenous resources and traditional knowledge passed on by their ancestors [7, 8]. High altitude regions where traditional fermented beverages are produced have been indicated (highlighted) on satellite imagery map of the Himalayan region (Fig. 1). In Fig. 2, an outline map of the Himalayan Region has been attached where various portions of twelve Indian states and UT of Jammu and Kashmir, Nepal, Bhutan and parts of Southern-Tibet (Tethyan Himalaya) are marked (Fig. 2A) followed by demonstrating traditional fermented beverages of those regions (Fig. 2B).

High-altitude health issues and Himalayan ethnoecology

High-altitude sickness (HAS) encompasses a spectrum of diseases such as acute mountain sickness (AMS); edema (high-altitude cerebral edema, pulmonary edema and peripheral edema or swelling of organs like hands, feet, and face); hypoxia; gastrointestinal, respiratory (pneumonia, influenza, tuberculosis etc.), urological and gynaecological infections; pain or inflammation in the body muscle and joints; cardiovascular diseases including hypertension, high pulse rate, heart attacks etc.; digestive problems; neurological diseases and disorders including loss of appetite, sleep problems, headache, loss of coordination, cyanosis, confusion, irrational behaviour, tightness in the chest, weakness, vertigo and hallucinations etc. [28–30]. Hackett et al. [31], Johnson et al. [32] and Ferrazzini et al. [33] were among the medical scientists who pioneered the discovery of medicines for acute mountain sickness (acetazolamide and dexamethasone). Although, till date the pathogenesis of this disease is poorly understood thus drug development process has been overlooked as well [28]. Kapoor et al. [34] reported use of some drugs for the treatment of acute mountain sickness (AMS) and high-altitude pulmonary edema. To the best of our knowledge, Himalayan natural products, plant-based formulations and high-altitude fermented foods or beverages were rarely evaluated for development of therapeutics particularly targeting HAS. Despite this, tribal communities residing in these regions heavily rely on these products to cope with the high altitudinal stresses. Additionally, there are ethnomedicinal claims among both locals and tourists regarding the effectiveness of these traditional remedies in alleviating symptoms associated with high-altitude sickness. Mountains and high plateaus cover about one fifth of the Earth's surface which are habitat for 300 million people, countless species of animals and plants. At least 150 million people live permanently above 2400 m. Then there are millions of transient or itinerant populations from lower elevations who occasionally visit high-altitudes for travelling, trekking, climbing, skiing, and other activities [35]. Acute mountain sickness (AMS), high-altitude cerebral edema (HACE) and high-altitude pulmonary edema (HAPE) are well-known syndromes encountered at high altitude (> 2500 m), which are commonly referred to as "altitude sickness". AMS may associate with headache, nausea, dizziness, fatigue, insomnia etc. and may worsen and progress to HACE, characterized by mental changes and/or ataxia. HAPE (cough, chest discomfort, breathlessness on minimal exertion, tachypnea, and tachycardia) can also result from the complications of AMS, or it may present independently [31]. These well-recognized medical problems at altitude have been extensively discussed and reviewed [35–37]. In the Himalayan region, researchers highlighted the tribal traditional practices which are claimed to be useful to treat a range of altitude sickness [7, 38–40].

Professor Dr. Buddha Basnyat a clinician and researcher in infectious diseases and high-altitude medicine did pioneer research on high-altitude sickness and medicine in Nepal and Himalayas perspective. Basnyat et al. [42], recently reviewed various acute medical problems in the Himalayas outside the setting of major high-altitude sickness experienced in the Himalayas. They have mainly highlighted neurological conditions, such as, visual conditions, pulmonary conditions, and miscellaneous conditions. In the Himalayas, acute medical problems are encountered apart from AMS and the two types of altitude edemas. Many of these conditions are also associated with hypoxia and can occasionally resemble the major high-altitude illnesses such as AMS, HAPE, and HACE. Dawadi et al. [43] reported medical problems in Himalayan porters who have been accompanying trekkers and climbers to the high altitude since the earliest expeditions in the Himalayas. According to Dawadi et al. [43] they are prone to high-altitude illnesses such as acute mountain sickness, high-altitude pulmonary edema, high-altitude cerebral edema; and other illnesses such as diarrhoea, respiratory illnesses, trauma/musculoskeletal injuries (due to wearing improper footwear and heavy load carrying), frostbite/cold injuries, visual conditions like uncorrected refractory errors and photokeratitis, infections etc. Apart from the very common gastrointestinal and respiratory infections, others such as enteric fever, dengue, typhus, viral hepatitis, and influenza are also frequently encountered in those traveling to high altitudes [44, 45]. Moreover, tuberculosis remains a

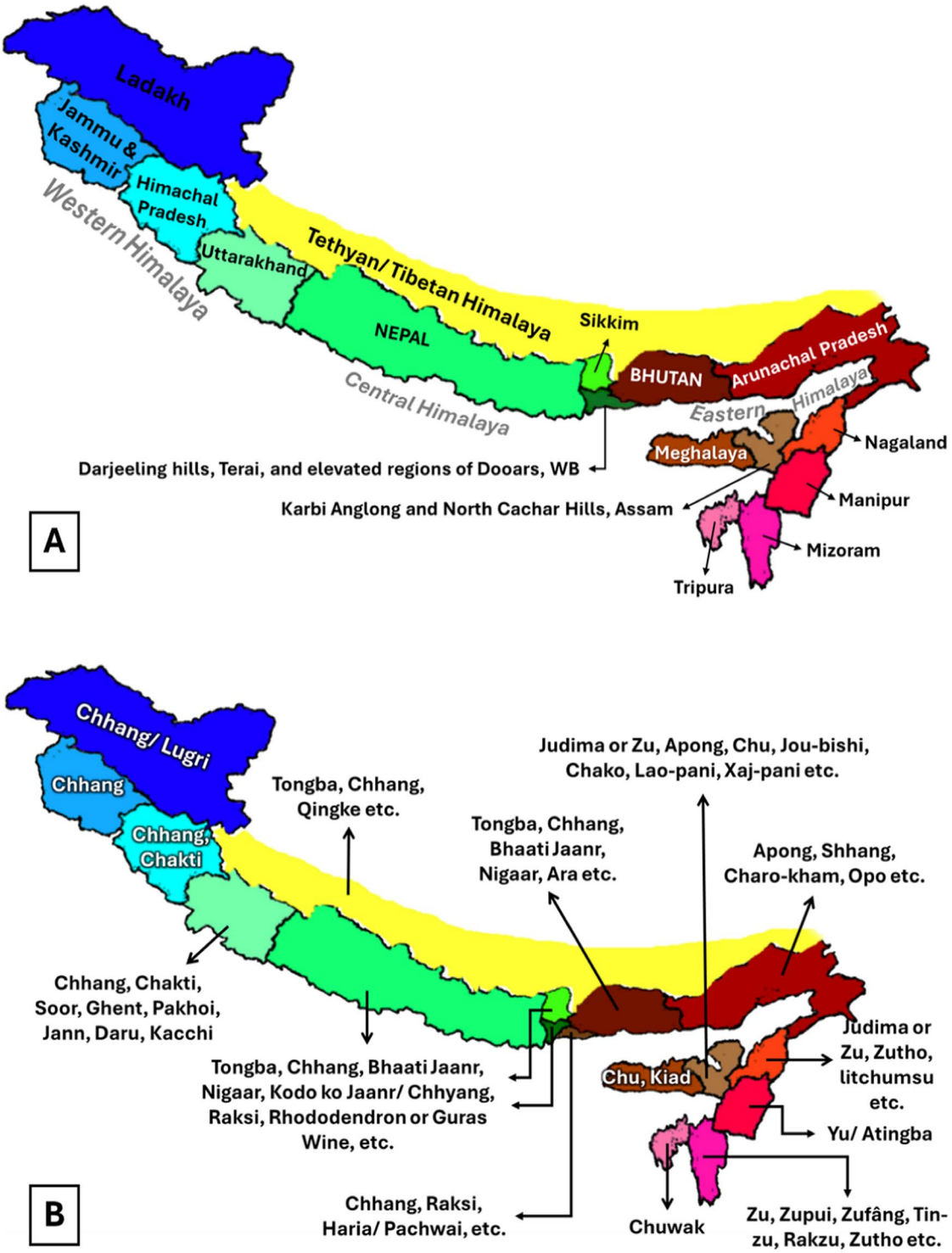

Fig. 2 **A** Different administrative regions within the Himalayan region [one union territory and twelve states of India (UT of Jammu and Kashmir, Ladakh, Himachal Pradesh, Uttarakhand, Darjeeling and Kalimpong districts of West Bengal, Sikkim, Dima Hasao or North Cachar Hills and Karbi Anglong districts of Assam, Meghalaya, Arunachal Pradesh, Nagaland, Mizoram, Manipur, Tripura); Nepal; Bhutan; and parts of southern Tibet]. **B** Region specific fermented ethnic beverages (as listed in Table 2) from the Himalayas etc.

significant public health concern in Nepal, with approximately 44,000 new cases reported annually nationwide, and an estimated 10,000 cases still undetected or unreported [43]. A cough in a porter could be attributed to tuberculosis rather than the prevalent 'Khumbu cough'. Additionally, mitral stenosis resulting from rheumatic heart disease, a common infection in Nepal [46], may remain asymptomatic at lower altitudes. However, due to pulmonary hypertension at high altitudes, high-altitude inhabitants may develop pulmonary edema, potentially leading to misdiagnosis as high-altitude pulmonary edema (HAPE). Table 1 has been prepared following Basnyat et al. [42], Ericsson et al. [29], Chen et al. [30], Dawadi et al. [43], and Majumder et al. [28] where various altitude-sicknesses of the Himalayas have been listed.

In India, the major portion of ethnic communities live in the hilly regions of the Himalayas stretched from Ladakh to Arunachal Pradesh. The Himalayan region, which includes Jammu and Kashmir, Ladakh, Himachal Pradesh, Uttarakhand, Nepal, Sikkim, Darjeeling hills, Bhutan, Arunachal Pradesh, and some hilly regions of northern Assam, is host to the world's highest ecosystems [7, 38, 39]. The ethnic tribes of the Himalayan region, living in high-altitude areas, are distinguished for their traditional knowledge and food preferences shaped by their geographic conditions and lifestyle [40]. Himalayan region is a centre of diverse food cultures comprising fermented ethnic foods and alcoholic beverages which are products of tribal traditional knowledge and safeguarded as their asset and only passed from past to future generation. On the other hand, fermentation of foods is basically carried out to preserve locally grown crops and harvest in the Himalayan region where remote access, cold climate induced stress, soil fertility etc. are crucial high-altitude threats. Poudel and Adhikari [41] discussed psychosocial factors in the Himalayas are linked to bio-geographical barriers, including limited healthcare facilities, harsh climate and terrain,

Table 1 Various high-altitude related sicknesses in the Himalayas

Category of the disease	Name of the disease
Classic altitude illnesses	Acute mountain sickness (AMS)
	High-altitude cerebral edema (HACE)
	High-altitude pulmonary edema (HAPE)
Other pulmonary conditions	Pulmonary embolism
	Periodic breathing
Infections	Gastrointestinal infections, neurological infections, respiratory infections, dermatological infections, urological and gynaecological infections etc.
Inflammatory conditions	Pain
	Peripheral edema
Cardiovascular health conditions	Rheumatic heart disease
Neurological diseases and disorders	Subarachnoid haemorrhage
	Transient global amnesia
	Stroke and transient ischemic attacks (TIA)
	Seizures
	Suddenly symptomatic Brain tumours
	Migraine
	High-altitude syncope
	Guillain–Barré syndrome
Visual conditions	Cortical blindness
	Amaurosis fugax
	Lateral rectus palsy
	Retinal haemorrhage
	Radial keratotomy at high altitude
Miscellaneous problems	Drug- and alcohol-related problems
	Hypothermia and dehydration
	Carbon monoxide poisoning
	Psychological problems
	Asthma and myocardial infarctions

transportation issues, educational constraints, economic factors, low awareness and health-seeking behaviours, as well as reliance on traditional medicine practices. In their study on "Diabetes in the Himalayas" they described that despite scepticism towards modern healthcare, traditional healers possess intimate knowledge of community members' backgrounds, enabling them to provide personalized care. However, traditional methods may offer some benefits but scientific evaluation of traditional therapeutics, integrating traditional practices with modern healthcare and providing traditional healers adequate training in contemporary medical practices would be essential for advancing the healthcare system in the high-altitudes. Moreover, fermented beverages are important elements of culture, tradition, economy, and nutrition of tribal people and in the context of ethnoecology in the overall Himalayas. In remote areas of the Himalayas where availability of important functional food is a challenge throughout the year, there these fermented foods and beverages can be considered essential for food and nutritional security of the region. And this reliance upon fermented food has been sustained due to cultural adaptation for consumption and the inherent preservation qualities of these products, as coined by Tamang et al. [40].

Tibetan and Nepalese ethnic groups such as, Sherpa, Rai, Tamang, Lepcha, Limbu, Gurung etc. from Singalila ridge of the Eastern Himalaya (altitude: 2400–3600 m) prepare and consume traditional alcoholic beverages like, *tongba*, *chhyang*, *nigaar*, *raksi* etc. [21]. Majumder et al. [21, 22, 26, 28, 47] collected those beverages and analysed high-altitude sickness healing potential of the beverages through in vitro, in silico and metabolomics research. Majumder et al. [21] described traditional drink *raksi* as "an element of ethnopharmacology of high altitude". Local people from ethnic communities residing in the Singalila ridge of the Himalayas, as well as visitors who have successfully treated altitude illnesses using traditional medicines, claim the therapeutic properties of these beverages [21, 26]. According to Seale et al. [48], Tamang et al. [7] and Rawat et al. [5], indigenous people living in the high-altitude cold regions around the world usually believe that traditional alcoholic beverages help treat diseases and generate energy/warmth in the body to tolerate the extreme cold temperature of hilly areas. However, it is widely recognized that moderate consumption of traditional alcoholic beverages can have health benefits, but excessive and frequent intake of alcohol can induce adverse health problems [49].

In this context, high-altitude related health issues referred to as any health challenge faced by tribal communities residing in remote areas of the Himalayas that is beyond altitudinal-stress induced illnesses (hypoxia/AMS/edema/blood pressure/infection etc. as described above). Because of the remoteness of these regions and the limited access to conventional healthcare facilities, tribal populations often rely on traditional healing practices and natural remedies to address their healthcare needs. Therefore, it becomes imperative to gather and document every reported medicinal claim associated with the Himalayan traditional fermented beverages and meta-analysis of available scientific validation for a holistic understanding of the therapeutic potential of traditional healings and their relevance in addressing the diverse health concerns encountered at high altitudes.

Substrates, starters and fermentation

Several ethnobotanical studies on traditional alcoholic beverages prepared by the Himalayan tribal communities have been published [7, 8, 50]. According to various studies, these traditional alcoholic beverages completely plant based because both substrate materials (cereals, fruits and flowers) and starters contain various plant parts that source nutrients, microbes, preservatives and medicinal compounds [5, 26, 51]. Therefore, these beverages not only contain edible alcohols and other fermented metabolites but also contain bioactive phytochemicals and micronutrients like vitamins and minerals [2, 22, 52, 53]. Finger millet/*kodo* or ragi, rice, wheat, maize and barley are used as substrates in the preparation of cereal based traditional beverages mostly in the Himalayan high-altitude regions, sub-Himalayan foothills and other hilly terrain and remote places [7, 22]. Rhododendron flowers or *lali guras* (*Rhododendron arboreum* Sm.) is also used as potential brewing substrates traditionally. In the rhododendron growing regions of the Himalayas (Uttarakhand, Himachal Pradesh, West Bengal- Singalila ridge and Sikkim), guras (wine from rhododendron's flower petal) is a popular drink among the local inhabitants and tourists [47]. Fruits are often used as substrates to brew indigenous alcoholic drinks in the Himalayas, for example: peach wine in Bhutan and wines from grapes, cherries, pineapples, guavas, jackfruits, blackberries, oranges, pears and peaches in North East India. Based on the use of raw materials and preparation methods, these beverages can be classified into various types such as food-beverage (nutrient rich thick paste of less-fermented cereals consumed as staple food), beverage (filtered version of the liquefied more-fermented food-beverage), liquor/spirit (distilled version of the fermented beverage) and wine (mainly fermented fruit and flower products) [54–56]. Traditional alcohol brewing is a home-based industry run by tribal women using indigenous knowledge of the fermentation process. Tribes of the high-altitude Himalayan region have developed their own cultures for the preparation of fermentation-based

alcoholic beverages using the available natural resources in the region [57]. The preparation of traditional beverages is not only a means of livelihood in the hill regions but also an important household-cum-societal drink associated with religious ceremonies [58]. As listed in Table 2, quite a few indigenous Himalayan beverages are known by different local names, for example *chaang* or *chhyang* prepared with rice is referred to as *bhati jaanr* by Nepalese while Tibetan *tongba-* a finger millet based beverage is often termed as *kodo ko jaanr*. However, all tribes across the Himalayan region mostly share a similar method, which includes cooking of raw material, drying, and incorporation of starter culture, fermentation, and the extraction of the final product.

Starter cultures are traditionally prepared cultures of fermenting microbes which are used to brew alcohol or fermented foods from starchy materials. Himalayan ethnic groups of people prepare amylolytic starter cultures using their traditional knowledge for brewing fermented beverages for long periods. These starters are typically dry cakes made from ground rice and wheat with flattened or round balls like shapes which source consortia of saccharifying and alcohol-producing yeasts, filamentous molds and lactic acid bacteria [7]. Asian ethnic starters have different vernacular names such as *marcha* in India and Nepal, *ragi* in Indonesia, *bubod* in the Philippines, *chiu*/ *chu* in China and Taiwan, *loogpang* in Thailand, *nuruk* in Korea, and *men* in Vietnam, which are used to ferment on rice and cassava or other cereals in Asia [7]. The traditional knowledge of alcohol production by "starter culture" and technique of distillation using traditional apparatus (Fig. 3) are well recognized in the Himalayas [7, 47].

The consortia of starter cultures are preserved in ground rice or wheat balls prepared with additive herbs that altogether function as a source of starch and glucose to supplement nutrients or carbon sources to the culture [7, 23]. The traditional technique of subculturing desirable inoculant from previous batches helps to preserve beneficial and essential fermenting microbes for fermentation. *Marcha* is a unique-looking starter from Himalayan region distinguished from other starters in Asia. This starter is primarily used to ferment rice, grains, and milk, producing local alcoholic beverages or fermented dairy products. Techniques of *marcha* preparation indicates region specific ethnic knowledge of the Himalayan tribal people. The outer part of the starter is usually wrapped in fern fronds, with the sporangia in contact with the surface (Fig. 4: *Marcha* or *Hamei*). According to Tamang et al. [7] germination of spores provides warmth that helps to maintain the culture condition or temperature to endure cold climate of the high-altitude for sustaining the growth fermenting microbes. These

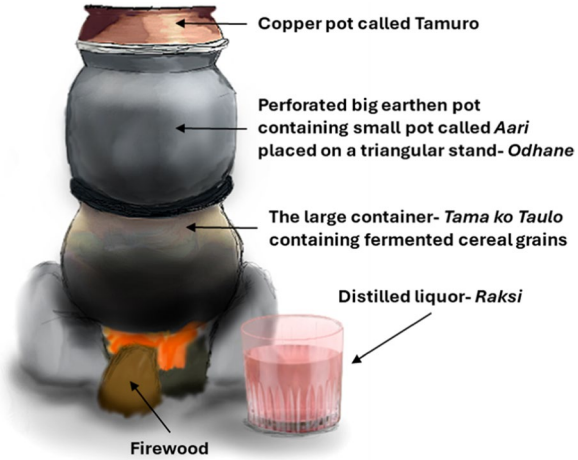

Fig. 3 Artistic illustration of the traditional distillation apparatus used for distillation of *raksi* beverages and different parts of the apparatus from bottom to top as described with their functions i.e., *Tama ko Taulo* or *Phosi-* the large copper container/boiler at the bottom which contains fermented and liquified cereal grains; perforated big earthen pot (*Paini*) at the middle that contains a small earthen alcohol collection pot- *Aari* placed on a triangular iron stand where actually distilled liquor *Raksi* is collected; and copper pot called *Tamuro* at the top that contains water and functions as a condenser or *Bata*

ferns [*Glaphylopteriolopsis erubescens* (Wall ex Hook.) Ching] locally called *pire uneu* are found abundant in the Himalayas [7]. However, the basic preparations of such starters are quite similar across the Himalayas. Contamination from undesirable microorganisms may affect *marcha*'s quality, therefore natural antimicrobials such as red chilies, gingers, charcoals etc. are used as preservatives during storage of dried *marcha* [7, 59]. According to Hesseltine [59] spices inhibit the growth of many bacteria and molds, which facilitates the selective growth of desired microbial population needed for fermentation.

Marcha is the most popular ethnic starter used to produce fermented cereal (rice/wheat/maize/millets/blended grains)-based alcoholic beverages like *jnad* or *jnaar*, *chhyang* or *chhaang*, *nigaar*, *tongba* etc. in the Himalayan regions of India which is the Nepali term while different ethnic communities of the Himalayas call it by their vernacular names such as *phab* (Tibetan), *poo* (Drukpa), *khesung* (Limboo), *bharama* (Tamang), *bopkha* or *khabed* (Rai), *buth* or *thanbum* (Lepcha), *manapu* (Newar), *hamei* (Meitei), *thiat* (Khasi), *humao* (Dimasa), *pham* and *ipoh* (Apatani), *bakhar* (people of Himachal Pradesh and other places of North- India), and *balan* (people of Uttarakhand in India) and *ranu dabai* (tribal people of sub-Himalayan tea belt and forests of Terai and Dooars of West Bengal).

Other important Himalayan ethnic starters are: ***dhehli*** (also known as *roat* in Sirmaur region) the fermentation

Starter culture *Marcha* and fermented wheat grains from Darjeeling

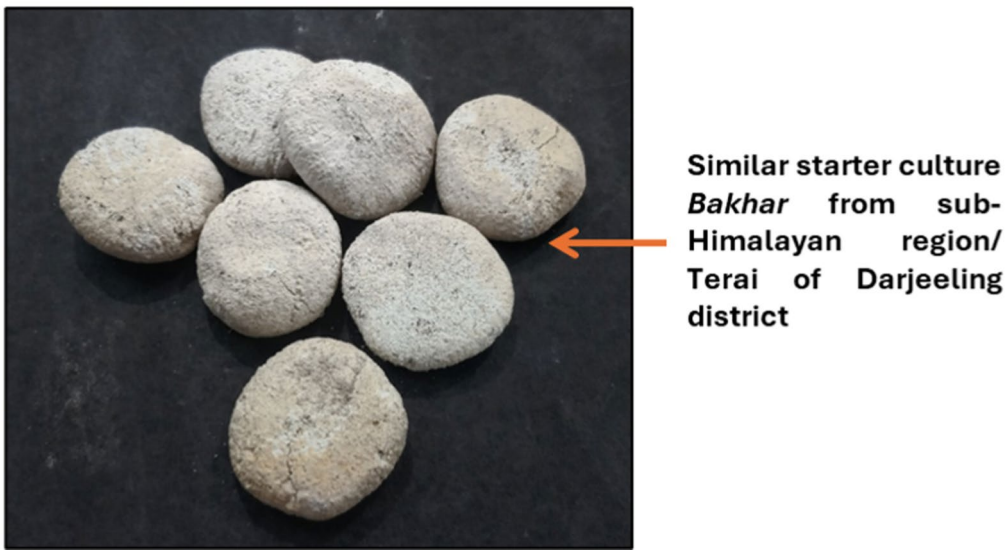

Fig. 4 Different amylolytic traditional starter cultures used to ferment ethnic beverages in Himalayan region for example *Marcha* (top) from high-altitude region of Darjeeling prepared as dried fermented glutinous rice balls wrapped with fern fronds and *bakhar* or *Ranu dabai* (bottom) prepared by tribal people of sub-Himalayan tea belt and forests of Terai and Dooars of West Bengal. Both of these dried starter balls are prepared from pounded overnight soaked glutinous rice with additives such as herbs and other plant parts used as ethnomedicines by local communities

starter for *sura* in Himachal Pradesh; ***keem*** (flat, dark-brown starter cake from Uttarakhand); ***balam*/*balma*** (wheat-based starter of Garhwal and Kumaon region of Uttarakhand); ***humao*** (traditionally prepared amylolytic starter from Assam); ***e'pob*/ *siiyey*/ *aopo pitha*** (starter in Arunachal Pradesh and Assam); ***hamei*** (starter for *atingba*, an alcoholic beverage in Manipur); ***malera*/*khameer*** and ***treh*** (from Himachal Pradesh); ***wanti*/*wansi*** (traditional starter from West Garo hills, Meghalaya); ***bakhar*** (traditional starter used to brew *pachwai* or *handiya* by tribal people residing in tea gardens and forests of sub-Himalayan Terai and Dooars region) etc. (Fig. 4) [5, 7, 8].

For preparation of *chhang*, clean rice or other preferred substrates such as *kodo* or wheat or a blend of multi-cereals is cooked and spread on a bamboo mat for cooling, and then starter (powdered *marcha*) is sprinkled (2–4%) over it. After that the grounded starter culture "*marcha*" is mixed uniformly with the cooked and cooled substrate. The substrate-starter mixture is kept in a vessel or earthen pot for 24–48 h at room temperature capped tightly with woollen clothes to provide the optimum incubation temperature to allow saccharification. The process of saccharification is usually completed in 2–3 days in summers and 6–7 days in winters. After this step, the texture of the mixture appears to be cream-like slurry. Further, this slurry was transferred to sterilized pots. To this slurry, water was added, and the mixture was allowed to ferment. After fermentation, a thick paste is prepared from the fermented mixture by stirring with a wooden or bamboo stirrer and consumed as a food beverage [7, 22, 23, 26]. The same culture, without smashing the *kodo* millet grains (as done for *chhyang*), is incubated for further aging to prepare *tongba*

which is offered after adding hot water [22, 26]. Lastly, distillation of different fermented broths is conducted to prepare *raksi* which is carried out using traditional distillation apparatus (Fig. 3). *Bhaati jaanr* (rice beer or *chhyang*), *poko*, *makai* (maize) *ko jaanr*, *kodo* (finger millet) *ko jaanr*, *gahoon* (wheat) *ko jaanr*, fermented masses of buckwheat, potato, canna, and cassava roots, fermented *guras* (rhododendron wine) are distilled for 2–3 h continuously over firewood in an earthen oven to prepare *raksi* which is often fortified with ethnomedicinal plants like *khokim* root, *chimphing* flower, *guras* or rhododendron petals, *timur* berries and various herbs.

Ethnomedicinal properties of different Himalayan ethnic fermented beverages

The concept of "ethnofoodology" is to understand the indigenous knowledge of people on production of culturally and organoleptically acceptable foods followed by further analysis to characterize the ethnic food. Fermentation in the Himalayas signifies traditional knowledge on food preservation shared by the tribal people, and this is an immense part of food management in the mountains. The ethnofoodology research revealed that Himalayan foods are very distinctive and diverse, enriched with a plenty of traditional foods which include cereal-based fermented beverages like, *tongba* or *tumba*, *chhyang* or *chhaang*, *nigaar*, *raksi* etc. (Fig. 5) [60]. There are more than 200 varieties of unique ethnic fermented foods and alcoholic beverages in the Eastern Himalaya (Nepal, North East India and Bhutan), which are not very popular or commercialized outside the region [61]. Since these beverages are strongly intertwined with the origin, habitat, religion, and overall tribal way of life; ethnic communities tend to consider these ethnic drinks as an integral part of their cultural heritage. Consequently, they strive to safeguard their long standing traditional customs and preserve their secret age old traditional knowledge of brewing, shielding it from external influences and exposure. Yet, scientists and researchers have investigated and documented various aspects including preparation methods, ethnomedicinal claims, laboratorial characterization and evaluation of therapeutic properties of some important Himalayan traditional beverages.

Traditional alcoholic beverages consumed by the local tribes in the Himalayan region are not only related to rituals and occasions but also known to provide increased nutrients, such as proteins, vitamins, added minerals, phytochemicals, phytosterols, and dietary fibres to the consumer [62]. Functional foods provide health benefits beyond basic nutrition. These foods improve health and increase bioavailability of components having beneficial effects like removal of toxic substances by biochemical processes [63]. Some of the explored fermented beverages of the Himalayas have been complied in Table 2. Apart from their cultural and social relevance, these beverages are consumed in therapeutic purposes to treat ailments like high-altitude sickness, inflammation, infections, diarrhoea, jaundice, kidney stone etc. which have also been noted Table 2. Tribal people, consumers, ethnobiologists and other researchers also acclaimed high-altitude sickness healing properties of certain beverages as mentioned in the table. Another important scope of traditional fermented beverage research is the study on fermenting microflora. However, knowledge of the fermenting microflora and metabolomics of these beverages is scanty which is mostly concentrated in the Eastern Himalayas. Besides having functional food properties, traditional fermented beverages contains various

Fig. 5 Some famous fermented ethnic beverages of the Himalayas. **A** *Tongba/ kodo ko jaanr* (from Ilam district of Eastern Nepal), a common Tibetan traditional finger millet (*kodo*)-based mild alcoholic beverage, **B** *Chhang* or *chhyang*- the most popular rice-based alcoholic beverage (5–7% abv) of the Himalayan region, from Ladakh to Bhutan (picture source: https://kodoko.co.uk/local-alcohol-and-herbs-from-nepal/). **C** *Kodo ko Nigar*- yellowish supernatant liquid obtained from fermented and liquified finger millet that contains high alcohol, **D** *Guras/* Rhododendron wine (from rhododendron growing Singalila ridge of the Himalayas), **E** Distilled liquor *Raksi*- one of the most popular ethnic alcoholic drinks of the Himalayas (also a common term for alcoholic drink in Nepali) with distinct flavour which is prepared by distillation of traditional fermented cereal beverages

Table 2 Himalayan ethnic fermented beverages and reported ethnomedicinal properties with special reference to their high-altitude sickness healing potentials

Name of beverage	Region	Ethnomedicinal properties	Reference
Chhang/ Lugri	Himachal Pradesh; Uttarakhand; Nepal; Darjeeling hills of West Bengal, Sikkim; and parts of Tibet	Functions as staple food and provides energy, anti-inflammatory-treatment of arthritis and joint pain and protection against cold, antioxidant, antibacterial (against high-altitude infections), anti-inflammatory, cardioprotective, neuroprotective, hepatoprotective, high-altitude sickness (hypoxia and acute mountain sickness) healing properties etc	[5, 7, 8, 22, 25, 54, 57, 64–68]
Sura/Sur	Himachal Pradesh	Protection against cold	[5, 54]
Soor, Ghenti and *Pakhoi*	Uttarakhand	Protection against cold	[5, 69]
Jann, Daru and *Kacchi*	Uttarakhand	Treatment of fever, dysentery, cough and cold, stomach ailments; cholera, treating weakness; being very energy rich it protects from cold at high-altitude regions	[5, 50, 57, 69, 70]
Chakti	Himachal Pradesh and Uttarakhand	Functions as high-calorie staple food	[5, 25]
Bhaati Jaanr and *Nigaar*	Nepal, Indo-Nepal Singalila ridge Darjeeling hills of West Bengal, Sikkim	Functions as high-calorie staple food and remedy for ailing old individuals in villages, help in recovering strength	[7, 70, 71]
Tongba	Nepal, Indo-Nepal Singalila ridge Darjeeling hills of West Bengal, Sikkim, Bhutan and parts of Tibet	Protection against cold and dehydration, moisture retention property in skin and body; antioxidant, antibacterial (against high-altitude infections), anti-inflammatory, cardioprotective, neuroprotective, hepatoprotective, high-altitude sickness (hypoxia and acute mountain sickness) healing properties etc	[22, 26, 28, 60, 72]
Kodo ko Jaanr/ Chhyang	Nepal, Indo-Nepal Singalila ridge Darjeeling hills of West Bengal, Sikkim	Most nutritious drinks with high calories and vitamins consumed as staple food; antioxidant, antibacterial (against high-altitude infections), anti-inflammatory, cardioprotective, neuroprotective, hepatoprotective, high-altitude sickness (hypoxia and acute mountain sickness) healing properties etc	[7, 22, 28, 70]
Raksi	Nepal, Indo-Nepal Singalila ridge Darjeeling hills of West Bengal, Sikkim	Antioxidant, antibacterial (against high-altitude infections), protect against respiratory illness, anti-inflammatory/ pain relieving property, cardioprotective, gastroprotective, neuroprotective, hepatoprotective, high-altitude sickness (hypoxia and acute mountain sickness) healing properties, anticancer etc	[21, 22, 28]
Guras/Buransh Wine and *Raksi* (Rhododendron flower based)	Rhododendron growing regions of Nepal, Indo-Nepal Singalila ridge Darjeeling hills of West Bengal, Sikkim	Anti-inflammatory or pain relieving properties, cardioprotective and gastroprotective (anti-diarrhoeal) activities, anti-viral (celebrated for anti-coronavirus potentials based on research findings during covid-19	[47, 73]
Haria/ Pachwai	Tea belt of sub-Himalayan foothills (Terai and Dooars) of West Bengal	Gastro-protective (dysentery, diarrhoea, acidity, vomiting), immunostimulatory, antioxidant, anti-inflammatory, antibacterial, antifungal, neuroprotective, anticancer, hepatoprotective, cardio-protective (hypotensive), antiaging etc	[74–77]
Tchang/ Jhar and *Rokshi*	Sikkim	Probably similar to *chhang*, *jaanr* and *raksi*	[7, 69]
Judima or *Zu*	Assam; Nagaland; Mizoram	Rejuvenating and revitalizing properties; antioxidant, antifungal, antibacterial, neuroprotective, antiaging, and anti-inflammatory properties	[5, 7, 8, 70, 78, 79]
Apong	Assam and Arunachal Pradesh	Treat kidney stone and protection against cold	[5, 8, 80–84]

Table 2 (continued)

Name of beverage	Region	Ethnomedicinal properties	Reference
Zutho	Nagaland and Mizoram	Boost immune system, lower blood insulin level, prevent loss of appetite, lower blood cholesterol and prevent infections	[5, 8, 70]
Yu/ Atingba	Manipur	Treat infertility factors, irregular menstrual flow, menstrual inflammation, low nourishment, obesity, loss of appetite; restorative properties; strong anti-inflammatory and anti-obesity properties	[5, 7, 8, 85]
Chu	Assam and Meghalaya	Antioxidant and antibacterial	[5, 86, 87]
Qingke	Qinghai-Tibetan Plateau	Anticarcinogenic and antidiabetic properties	[88–91]
Jou-bishi	Assam	Prevent various illnesses including jaundice and urinary tract infections caused by *E. coli*	[5, 8, 28, 70, 83, 84, 92, 93]

medicinal compounds sourced from both fermenting microbes and additive medicinal plants. Microorganisms, including probiotic lactic acid bacteria like *Lactobacillus*, *Leuconostoc* and yeasts like *Saccharomyces*, *Pichia* and mold like *Rhizopus*, have been reported in cereal-based alcoholic beverages of the Eastern Himalayas which not only produce alcohol but also biosynthesize other bioactive secondary metabolites [5, 26, 51].

There are many other ethnic fermented beverages beyond the ones listed above which remained underexplored in the Himalayan and sub-Himalayan regions and need to be surveyed, documented and scientifically evaluated. Roy [94] and Rawat et al. [5] has mentioned some of the beverages for example *kiad* and its starter *thiat* (a rice-based fermented beverage of Khasi and Jaintia tribe in Meghalaya); *shhang* or *charo-kham* and its starter *ipoh* (a barley- based fermented beverage of Karbi tribe in Arunachal Pradesh); *opo* (burnt rice based fermented beverage of Adi-Galo, Nyshing and Mishmi, tribes of East and West Siang, Lohit, Changlang, Upper and Lower Subansiri districts of Arunachal Pradesh); *litchumsu* (rice beer prepared by Ao tribe in Nagaland); ethnomedicinal (preventative of cold) *chuwak* (a rice-based fermented beverage of Kalai tribes in Tripura Rice); *chako* (rice-based alcoholic beverage from Assam); *lao-pani* and *xaj-pani* (from Assam); *zu* of different grades such as *zupui* (main alcoholic beverage), *zufâng* (sweet rice beer), *tin-zu* (strong undistilled rice beer) and *rakzu* (strong distilled rice beer*)* which is made from fermented rice, millet, or maize (from Mizoram); *ara* (from Bhutan) etc. [5, 84, 95, 96]. Figure 5 represents photographs of selected beverages studied in this review. Available scientific validations of the above-mentioned ethnomedicinal properties and high-altitude sickness healing abilities of the beverages have been described in the following section.

Scientific evaluations of high-altitude sickness healing and other medicinal properties of the beverages

Biochemical characterization of Himalayan fermented beverages

Researchers have conducted various in vitro, in vivo and in silico experiments to evaluate medicinal properties of the Himalayan ethnic beverages. Medicinal plants used to prepare starters and as additives in the beverages were also studied. Tamang et al. [7, 55] identified lactic acid bacteria (LAB), *Micrococcus* sp. and *Bacillus* sp. in Himalayan starter cultures which exhibit functional properties, such as enrichment of nutritive values, preservation of perishable products, probiotic properties, and antimicrobial properties and improvement of minerals bioavailability.

Arjun et al. [78] surveyed preparation of starter cake *humao* and ethnic beverage *judima* by the Dimasa tribe [92] in north Cachar Hills of Assam and Dimapur in Nagaland. They have identified and collected leaves of medicinal plants- *Piper betle*, *Buddleja asiatica*, *Hedyotis scandens* and *Acacia pennata* for the phytochemical screening of the starter cultures and laboratory preparation of *judima* for in vitro characterization such as estimation of alcohol, turbidity, carbohydrate and protein; thin layer chromatography; qualitative phytochemical analysis (tests for determination of phenols/ tannins, flavonoids, saponins, glycosides, steroids, terpenoids and alkaloids); DPPH assay for antioxidant activity; and short term cytotoxicity study using MTT assay. This study revealed that *judima* contains good amounts of protein, carbohydrate and free amino acids with high antioxidant activity.

Ghosh et al. [74] indicated the strong antioxidant property exhibited by *Lactobacillus fermentum* KKL1 strain, a LAB involved in fermentation of *haira*, a sub-Himalayan rice-based beverage [8]. Ray et al. [97] reported strong antimicrobial abilities, biofilm formation, and probiotic efficiencies of such rice-based alcoholic beverages suitable as health supplements. Shrub *Artemisia* sp. is used for the production of ethnic starter *phabs,* and that plant has various medicinal properties including antimicrobial properties against various pathogenic microorganisms existing in nature and thus contributing to the natural preservation of the product [98]. Probiotic potential of *chhang* along with the antioxidant properties is attributed to the presence of *Lactiplantibacillus plantarum* in *phabs* [8, 99]. Earlier, Basappa et al. [100] evaluated the nutritional composition of fermented finger millet (*Eleusine coracana* G.) or ragi (*chhang*) by *phab* where they reported an increase in some free amino acids in addition to the synthesis of extra amino acids. Moreover, higher levels of riboflavin, pantothenic acid and niacin and significant amounts of bioavailable minerals (Ca, P and Fe) were detected in *chhang* compared to unfermented finger millet along with fresh biosynthesis of cyanocobalamin during fermentation.

Ethnic beverage *sura* from Himachal Pradesh contains significant amounts of complex B vitamins, amino acids, and probiotic strains of LAB, offering nutritional and probiotic benefits [8, 24]. Additionally, methanolic extract of its starter *dhaeli* or *dheli* has been reported to exhibits antioxidant properties, enhancing its overall health benefits and supporting consumers' metabolic health. Thakur and Bhalla [24] studied alterations of biochemical profile during *sura* fermentation where they found increase of protein content; decrease of total carbohydrates and starch; and increase of reducing sugars,

amylase and protease activity and the level of B vitamins with the progress in fermentation.

Das et al. [101] worked with major rice beer varieties of Assam, namely *apong* (*poro* and *nogin*), *xaaj* and *joubishi*. Beside exploring microbiota and metabolites they have conducted biochemical experiments to determine alcoholic content, antioxidant properties (using DPPH and ABTS assays) and total phenolic content. The *joubishi* sample had the highest content of alcohol (19.33%) followed by sample *xaaj*. The alcohol content of *joubishi* and *xaaj* was high probably due to the use of local glutinous rice variety as substrate, which is corresponding to *sake*, the Japanese glutinous rice fermented beverage. All samples showed good antioxidant activities. Bhaskar et al. [102] reported positive effect of indigenous rice beverages of Assam on anxiety and spatial memory of mice by in vivo experiment and metabolomics and validated the claims by ethnic communities on its role on mood regulation.

Highly ethnomedicinal rhododendron flower (locally called *lali guras*)-based fermented beverages *guras* wine and *guras raksi* are claimed for anti-inflammatory or pain relieving properties, cardioprotective, gastroprotective (anti-diarrhoeal) and anti-viral activities [47, 73]. Majumder et al. [47] conducted qualitative and quantitative physicochemical and biochemical tests including antioxidant assays (DPPH and iodometric assay); antibacterial assay; and simulated gastrointestinal digestion for in vitro characterization of *guras*. Phytochemically rich unfermented *guras* decoction showed higher level of phenolics and fatty acid content but its poor gastrointestinal digestion exhibited a stable, hard-to-digest nature. While easily digestible fermented *guras* wine was determined as promising bioactive sample for exhibiting the highest antioxidant activity and it also showed antibacterial activity against *Bacillus subtilis* and *Klebsiella pneumoniae*- two major high-altitudinal threats [29].

Majumder et al. [22] also conducted in vitro experiments to evaluate ethnomedicinal potential of *kodo* (finger millet)-based traditional beverages such as *tongba*, *chhyang*, *nigar* and *raksi* samples, collected from Singalila ridge of the Himalayas. They have estimated high total phenolic content in *nigar*, *khokim raksi* and *tongba* (more 500 µg/mL gallic acid equivalent phenol) while highest free fatty acid was determined in *khokim raksi*. Antioxidant activity was evaluated using 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay, iodometric assay and in vitro anti-lipid peroxidation assay where *tongba* showed excellent antioxidant activity followed by *nigar* and *khokim raksi*. Sample *nigar*- a *kodo* millet fermented beverage showed promising antibacterial activity by inhibiting growth of all tested bacteria, i.e., *Escherichia coli*, *Klebsiella pneumonia*, *Staphylococcus aureus* and *Bacillus subtilis*. Acclaimed respiratory infection healing property of *nigar* was reflected in its antibacterial activity against *Klebsiella pneumoniae* and *Bacillus subtilis* (responsible for fatal pneumonia). Further inhibition of enteropathogenic *Escherichia coli* by both *nigar* and *khokim raksi* validated potentiality of these Himalayan beverages to prevent high-altitude infections. Further researchers carried out gas chromatography-mass spectrometry (GC–MS)-based metabolite profiling and elucidated the medicinal properties in metabolomic perspective.

Majumder et al. [22, 47] carried out another state-of-the-art experiment "in vitro gastrointestinal digestion" of fermented *kodo*-based beverages and *guras* (fermented rhododendron) beverages which figured out high bioaccessibility of the bioactive compounds in simulated human GI tract. Results of in vitro GID study showed that these beverages were entirely digestible and bioactive components (antioxidants, phenolics and lipid composition) are easily absorbable or bioaccessible within the GI tract. Recently, an in silico research has been carried out with metabolites from different ethnic beverages of Darjeeling Himalayas [28] which also predicted high bioavailability of the bioactives and molecular docking provided insights to their efficiency in alleviating major altitude illnesses (pulmonary edema and hypoxia); high-altitude respiratory infections; pain or inflammation; cardiovascular problems; gastrointestinal diseases and disorders; and high-altitude neurological diseases and disorders. Pharmacokinetics, ADMET results and docking scores by the metabolites corresponded high-altitude sicknesses healing properties of the beverages.

Ethno-microbiology of Himalayan fermented beverages

Microbial fermentation is a metabolic process where complex substrate products are converted into easily digestible products through the action of microbial enzymes and important secondary metabolites are biosynthesized based on the nature of microbes [47]. Traditional brewing involves fermentation of a starch-based substrate or sugar rich complex (cooked rice/barley/maize/millet/jaggery) by traditionally cultured starter microflora which gives production of ethanol, acetic acid, lactic acid, propionic acid, citric acid, succinic acid, glycerol and other edible fermented products. Study on microbiology of Himalayan starters and ethnic fermented beverages was initiated by Hesseltine [59] (on "anaerobic growth of molds isolated from fermentation starters" of Asia) and Tamang et al. [103] (on microbes of "traditional fermented foods and beverages of Darjeeling and Sikkim"); and was progressed by Tamang and Sarkar [104] (on microflora of amylolytic starter *marcha*); Thakur et al. [54]; Tamang et al. [55]; Rai and Kumar [105]; Tamang et al. [7]; Sha et al. [51]; Olee et al. [106] etc. Traditionally

prepared dry starters generally consist of filamentous molds, yeasts and bacteria that assist the fermentation symbiotically [107]. These organisms are recognized for their ability to secrete amylolytic enzymes, aiding in the conversion of complex sugars into simpler forms.

The duration of fermentation can range from two days to several weeks, depending on temperature, with consideration given to desired flavour, taste, and alcohol content [55, 64, 84]. Microorganisms capable of surviving and performing fermentation at low temperature (scientifically called bottom fermentation in the brewing of beer) are involved in brewing process carried out in the Himalayan region where temperatures are low. Brewer's yeast, filamentous fungi and bacteria are being employed through starter for the production of alcoholic and non-alcoholic beverages. Study of "ethno-microbiology" can be essential for many purposes from characterization of the starters and detection of beneficial and harmful strains of the microbiota to ranking of randomly collected starters from different brewers and further development of healthy starters from good strains. Among the primary yeast species *Saccharomyces* sp. is actually responsible for alcohol production [108]. Lactic acid bacteria (LAB), *Micrococcus* sp. and *Bacillus* sp. are the predominant among the bacteria involved in traditional beverage fermentation [55]. Tamang and Sarkar [104] identified microbes of *marcha* or *phab* (the common starter cake in the Himalayan region) as bacterial isolates of *Pediococcus pentosaceus* Mees.; yeast isolates of *Endomyces fibuliger* Lindner and *Hansenula anomala* (Hansen) Sydow and Sydow [presently classified as *Saccharomycopsis fibuligera* (Lindner) Klocker and *Pichia anomala* (Hansen) Kurtzman]; and mold isolates of *Mucor* sp. and *Rhizopus chinensis* Saito. The Bhotiya community from Uttarakhand uses *balam*—the wheat-based starter which was reported with thirty-two microbial isolates [5] dominated by *Bacillus* (two species) and yeasts (*Saccharomycopsis fibuligera*, *Kluyveromyces marxianus*, *Saccharomyces* sp. [67, 109]. Other microbes present in this starter were *Wickerhamomyces anomalus*, *Candida glabrata*, *Meyerozyma* sp., and *Pichia* sp. among yeasts; *Aspergillus penicillioides* and *Rhizopus oryzae* among molds. Studies also revealed fungi belonging to phyla Ascomycota and Zygomycota along with the genera *Saccharomyces*, *Zygosaccharomyces*, *Aspergillus*, *Aureobasidium*, *Mucor*, *Candida*, etc., in different traditional starter cultures of Himalayan region (*thiat*, *marcha*, *phut*, *humao*, *chowan* etc.) [51, 54]. Preparation of the indigenous starter cake involves either mixing of old starter powder (previous batch) with raw material or only the raw material as the source of desired microbiota. Tamang et al. [55] described health promoting properties of these microbes. *Saccharomyces* sp., *Lactobacillus* and *Bacillus* are beneficial microbes which are well documented and considered as potential probiotic candidates. Several research has explored genetic factors related to probiotic properties by studying starter cultures and fermented foods that revealed insights into how microbes contribute to probiotic qualities of traditional ethnic foods [67, 109, 110]. Tamang [111] who coined the term "ethno-microbiology", recently reviewed notable microorganisms present in Himalayan ethnic fermented beverage starters. Overall, the microbes involved in traditional beverage fermentation are of different types for example, filamentous molds (*Mucor*, *Rhizopus, Aspergillus*, *Amylomyces* etc.), yeasts (*Saccharomycopsis*, *Wickerhamomyces*, *Pichia, Candida* etc.), and various Gram-positive and Gram-negative bacteria [112–119]. Later, a range of bacteria from phyla Proteobacteria, Firmicutes, and Actinobacteria and genera *Leuconostoc*, *Lactobacillus*, *Acetobacter*, *Gluconacetobacter* etc. were revealed in fermented foods through high-throughput sequencing analysis [116].

Pradhan and Tamang [118] described probiotic properties of Eastern Himalaya's fermented beverages and reported functional properties of 37 LAB strains—one of the essential microbiotas isolated from dry starters of the Eastern Himalayas viz. *marcha*, *phab*, *paa*, *pee* and *phut*. The study found that a significant portion of LAB strains demonstrated high survival rates in acidic and bile salt conditions, with most showing the ability to produce β-galactosidase and phytase activity, but none had amylase activity. The majority also exhibited tolerance to ethanol. Genetic screening revealed various marker genes associated with gastrointestinal survival and nutrient (riboflavin and folic acid) synthesis.

Fermentation metabolomics—an emerging field of research on Himalayan fermented beverages

In the last thirty years, there has been exploration into the details of Himalayan ethnic fermented beverages, including ingredients such as substrate materials and starters, preparation methods, cultural significances, etc., whereas prior documentation primarily concentrated on identification of region-specific beverages and analyzing the socioeconomic perspectives associated to those [5, 7, 21, 60, 70, 106]. However, there is a lacuna in the literature worldwide regarding metabolomics of Himalayan ethnic beverages describing biosynthesis pathways of the metabolites. This area of study has been initiated over the past decade with the advent of metabolomic tools such as GC–MS, LC–MS (liquid chromatography-mass spectrometry), HPLC–MS (high-performance liquid chromatography-mass spectrometry) etc., along with metagenomic studied in food and fermentation science [21, 22, 120]. In the "Omics era", metabolomics and

meta-proteomics are powerful tools for analysing food fermentation, providing deep insights into microbial interactions, metabolic activity, and biochemical reactions. These methodologies, although relatively new, are crucial for understanding and enhancing the production of nutraceuticals and probiotics in fermented foods [120]. Metabolomics studies, in particular, help optimize fermentation processes, increase the bioavailability of beneficial compounds, and modify microbial strains for optimal metabolite production under different conditions [26, 120]. Identification of bioactive substances including trace elements in food samples is now possible due to upgraded chromatographic techniques and improved spectrometric methods. Sarkar et al. [120] recently reviewed metabolomics approach to ethnic fermented beverages, underscoring the gap in knowledge within Indian and subcontinental ethnofoodology perspectives compared to other regions of the world, which often focus on wine-centric studies i.e., fatty acid, phenolic, amino acid, terpenoid and other volatile profiling of wines. According to their study, the art of making wine is ancient, yet the molecular-level understanding of its various steps remains limited till date.

Overall, there are five types of fermentation that is classified according to their end products such as, alcoholic fermentation, lactic acid fermentation, acetic acid fermentation, propionic acid fermentation and butyric acid fermentation among which alcoholic and lactic acid fermentation (sometimes acetic acid fermentation, i.e., kombucha fermentation) are majorly involved in brewing industry and traditional alcoholic beverage fermentation. Voidarou et al. [121] thoroughly studied various classifications of fermentation. There are two types of fermentation (regarding the way the fermentation microorganisms are utilized): Firstly, natural fermentation that uses indigenous microorganisms of the substrate, only requiring the development of suitable conditions for their growth, function and suppression of competing microflora; secondly, controlled fermentation with starter cultures where desired microorganisms are added to outcompete others, making the fermentation process smoother and ensuring the product has consistent quality and taste. Beverage fermentation encompasses five main categories based on substrates or raw materials: (i) **grains** like rice, barley, corn, rye, millet etc. for producing beer, whiskey and traditional beverages around the world including Himalayan ethnic drinks- *chhang*, *nigar*, *tongba*, *raksi*, etc. [22, 26]; (ii) **fruit juices** (of apple, banana, cherries, berries, grapes, ginger, etc.) for producing cider, wines, cherry wine, ginger beer and ginger ale etc.; (iii) **vegetables** (potatoes, sugarcanes, cabbage, sauerkrauts, etc.) for producing vodka (in Poland), rum, sauerkraut juice etc. whereas, in the Himalayan region, fermented masses of potato, canna, and cassava roots are distilled to prepare alcoholic liquor- *raksi* [23, 103]; (iv) **milk** for producing many beverages such as *ayran*, *koumis*, *kefir* and buttermilk (*chanch*); (v) **other substrates** like tea leaves (for producing kombucha), honey (for producing mead), flowers (rose wine, rhododendron/ *guras* wine, *mahua* wine etc.), sugar, palm sap (for producing *tari* or *toddy*) etc. [21, 68, 121].

Fundamental alcohol fermentation tells about simple biochemical conversions such as production of ethanol, carbon dioxide and glycerol from sugars by the enzymatic actions of yeasts. Alcohol fermentation, named after its product- ethyl alcohol, primarily involves brewer's yeast (*Saccharomyces cerevisiae*) and occasionally anaerobic bacteria *Zymomonas mobilis*. These microorganisms convert glucose and other hexoses into ethanol and carbon dioxide via glycolysis or the Entner-Doudoroff pathway using enzyme ethanol dehydrogenase which serves as the primary model for the production of alcoholic beverages industrially and in small-scale settings for local or household use [7, 120]. Apart from saccharification and alcohol-production, molds, yeasts and some bacterial species mainly probiotic lactic acid bacteria present in the starters also biosynthesize important secondary metabolites that play major roles in providing flavour (mainly fatty acids and non-polar terpenoid derivatives), inhibiting the growth of undesired microbes (by producing antibiotics), and acidifying the fermenting substrates (with organic acids) [22, 118]. Lactic acid fermentation involves production of lactate by the key enzyme lactate dehydrogenase from various LAB (*Lactobacillus*, *Leuconostoc*, *Streptococcus*, and *Bifidobacterium*) acting on glucose as the substrate. Three pathways that can be employed by microorganisms include homofermentative pathway (production of 2 mol of lactate per mol of glucose), heterofermentative pathway (production of 1 mol of lactate and 1 mol of ethanol per mol of glucose), and Bifidum pathway (production of 2 mol of lactate and 3 mol of acetate per 2 mol of glucose) [7]. These biochemical alterations offer enhanced nutritional qualities which are commonly observed during fermentation of probiotic drinks. The traditional fermented drinks are often categorized as functional beverages because these provide additional health benefits other than sourcing basic nutrition just like functional foods. Moreover, fermenting microbes play a vital role in the development of flavour and aroma in final product and also help in biopreservation. Thus, these are often used for the production of several enzymes, flavouring substances, vitamins, etc., industrially [51, 55, 115, 116]. Traditionally prepared dry amylolytic starter cakes (*marcha*/*phab*/*phut*/*balma*/*humao* etc.) are cocultures of mixed microbiota (symbiotic colony) responsible for a

range of functions i.e., filamentous molds—for degrading starch of cereals to glucose; yeasts- for saccharification, liquefaction and ethanol production; and bacteria—for biosynthesis of probiotic metabolites with antimicrobial and other bioactivities [19, 23, 71, 112, 117–119].

As per recent reports, researchers have initiated GC–MS and HPLC analysis of Himalayan ethnic fermented beverages and already optimized sample preparation and extraction procedures. These studies were majorly carried out with samples from the Eastern Himalayan region of India while Nepal and western Himalayan parts in India lack such kind of research. Das et al. [95], Das et al. [101], Qian et al. [91], Majumder et al. [21, 22, 26] and Sarkar et al. [120] have reported metabolomics of different traditional beverages which included *tongba*, *chhyang*, *nigaar* and *raksi* (*khokim-raksi* and *chimphing-raksi*) from Darjeeling Himalayas; *apong*, *jou-bishi*, *lao-pani* and *xaj-pani* from High-altitude regions of Assam; *kiad* from Meghalaya; *judima* and *litchumsu* from Nagaland; *opo* from Arunachal Pradesh; and *qingke* from Tibet.

Bioactive metabolites of Himalayan ethnic beverages

A list of total 116 metabolites gathered from different research papers [21, 22, 26, 91, 95, 101] has been provided in Supplementary Table S1. Metabolites of various biosynthesis pathways have been noticed in these beverages including thirty six fatty acid derivatives; twenty one amino acid derivatives; ten phenolic components; eighteen terpenoids and steroids; two alkaloids; thirty one saccharide derived or fermented sugar derived products such as glycosides, fermented sugar alcohols, organic acids; and other compounds.

Majumder et al. [26] reported presence of ethyl *α*-D-glucopyranoside as major compound among twenty-five detected metabolites of *tongba* while abundance of sugar alcohol glycerol and other fermented carbohydrate derivatives followed by fatty acid derivatives were reported in ethnic beverages—*chhyang* and *nigaar* [22, 26]. Majumder et al. [22] reported large peaks of linoleic and oleic acids in *kodo* millet-based fermented beverage *nigaar* and distilled liquor *khokim raksi*, responsible for their high fatty acid content. Earlier, bioactive coumarins- meranzin and auraptene were determined in *khokim raksi* responsible for high-altitude sickness healing properties while *chimphing raksi* was rich in amino acids glycine and proline and derivative cyclic dipeptide cyclo-Gly-Pro. Terpenoid biosynthesis pathway derived plant metabolites or phytochemicals such as sandacanol, nootkatone, copalol, squalene, geranylgeraniol formate, etiocholanolone glucuronide, driman-8,11-diol, geranyllinalool and calamendiol were detected in two *raksi* samples supplemented with plant parts (*khokim* root and *chimphing* flower) [21]. Reportedly secondary metabolites of various biosynthesis pathways such as glycosides, phenolics, fatty acid and amino acid derivatives, terpenoids, alkaloids etc. were candidates responsible for antioxidant and antimicrobial properties of studied ethnic beverages from Singalila ridge (Indo-Nepal region) of the Himalayas [21, 22, 26]. Phenolics of single aromatic rings, i.e., tyrosol, phenylacetaldehyde, phenethyl alcohol and hydroquinone in *nigaar* and polyphenol coumarins- meranzin and auraptene in *khokim raksi* were responsible for their high TPC [22]. Earlier, Karki [122] reported abundance of phenolic content and fatty acids in a similar beverage—referred as traditional millet beer from Nepal. Qualitative test determined alkaloid in collected undistilled ethnic beverages (*tongba* and *chhyang*) from Singalila ridge which was further validated by GC–MS analysis through peaks of dihydroergotamine (2.7%) and nebularine derivative [22]. Similarly, detection of high glycosides in *tongba*, *chhyang* and *nigaar* by qualitative test was further validated by detection of corresponding peaks of major compound ethyl *α*-D-glucopyranoside [22, 26].

Majumder et al. [26] reported nine antioxidant compounds in *tongba* including major compound—cyclo (L-Leu-L-Pro), oleic acid, palmitic acid, *β*—sitosterol, phytol, neophytadiene, farnesol, tyrosol and actinomycin C2. The antioxidant metabolome of *nigaar* includes oleic acid, palmitic acid, β-sitosterol, neophytadiene, tyrosol, hydroquinone, phenylacetaldehyde, DDMP (4H-pyran-4-one, 2,3-dihydro-3,5-dihydroxy-6-methyl-), 5-hydroxymethyl-2-furfural, and succinic acid [26]. *Chhyang* was also reported to contain antioxidant compounds cyclo(L-Leu-L-Pro), phytol, neophytadiene, palmitic acid, oleic acid and β-sitosterol. Majumder et al. [21] reported major antioxidant components in *raksi* samples which were nootkatone, palmitic acid, squalene, geranylgeraniol, auraptene, linoleic acid, meranzin, cyclo-Gly-Pro and pGlu-Phe-Pro. Majumder et al. [22] also described hepatoprotective activity by *khokim raksi* and discovered bioactive compounds- nootkatone, squalene, auraptene and meranzin which might confer strong hepatoprotective actions. *β*-Sitosterol (detected in *tongba*, *chhyang* and *nigaar*), phytol (detected in *tongba* and *chhyang*) and tyrosol (detected in *tongba* and *nigaar*) can combat alcohol induced liver toxicity and prevent high fat diet-induced hepatic oxidative stress [22]. Major compound of *nigaar*- 5-hydroxymethyl-2-furfural and farnesol of *tongba* were also reported to possess hepato-protectivity. Antibacterial compounds of these beverages were tyrosol, phenyl acetate, phenylacetaldehyde, actinomycin C2 and farnesol, phenethyl alcohol, auraptene and lidocaine; Majumder et al. [21, 22, 26, 28] described their potential against various high-altitude respiratory and gastrointestinal infections.

Literature study revealed that biomolecules of Himalayan fermented beverage have potential to prevent and treat high-altitude illnesses including inflammation and pain, respiratory illnesses (COPD, lung injury, bronchitis, laryngitis, tracheitis, cough and cold and bacterial infections), cardiovascular diseases (hypertension, high LDL cholesterol and coronary artery disease), neurological stresses (nerve weakness, headache, dizziness, fatigue, shortness of breath, loss of appetite, sleep problems, vertigo etc.), altitudinal gastroenterological problems (mainly indigestion) and other diseases and disorders which can be collectively termed as altitude sickness [21]. Metabolites like auraptene and cyclo-Gly-Pro can help reduce edema, a common high-altitude sickness. Inflammation and high altitude often go hand in hand. Beverages like *tongba*, *chhyang*, and rhododendron wine or *guras*, consumed by trekkers and locals in regions like Singalila, may have anti-inflammatory properties due to compounds like auraptene and cyclo-Gly-Pro. These compounds can also offer pain relief and neurological protection. Majumder et al. [21] reported several respiratory protectives, cardioprotective, neuroprotective, anti-inflammatory, and antioxidant components in *raksi* which have properties to prevent various high-altitude illnesses. Auraptene, in particular, prevents hypertension and chronic gastritis, as well as exhibiting neuroprotective properties [21] relevant to high-altitude neurological ailments (anxiety, depression, etc. as described in the high-altitude sickness section). Ethyl *α*-D-glucopyranoside in *tongba* aids in retaining moisture in the body at high altitudes. Strong antioxidant and antibacterial compound phenylethyl alcohol was also detected as major compound of all traditional rice beers (*apong*, *jou-bishi*, *lao-pani* and *xaj-pani* from High-altitude regions of Assam; *kiad* from Meghalaya; *judima* and *litchumsu* from Nagaland; *opo* from Arunachal Pradesh) from North East Indian Himalayan region as characterized by Das et al. [95]. Moreover, studies concerning beverages from North East India and Tibetan liquor *qingke* primarily emphasized the aromatic constituents rather than their medicinal properties. Eastern Himalaya's famous *guras* wine and its *raksi* (most popular beverages in Singalila ridge) have recently been reported for anti-inflammatory activity due to presence of anti-inflammatory phytochemicals (quinic acid; clionasterol; l-(+)-ascorbic acid, 2,6-dihexadecanoate; d-sorbitol; cis-cinnamic acid; tyrosol; lupeol; methyl commate A etc.) sourced from the substrate- rhododendron flower [123].

Conclusion

The Himalaya is an exclusive and untapped resource in more ways than one. The culinary and ethnomedicinal traditions of indigenous tribes inhabiting the Himalayas have long been integral to their cultural heritage. Related practices have been upheld and passed down through generations, fostering a profound sense of connection between the community and its natural environment. An extensive array of traditional healing techniques using local flora or herbs have been trusted and revered, even over modern medicines sometimes, as not only remedies but also spiritual practices. Fermented foods and beverages hold deep cultural significance within the diverse ethnic communities of the Himalayas and world. Furthermore, culinary traditions have helped these communities adapt to the stress of drastic seasonal shifts and harsh environmental conditions of the high altitude. From ethnobiological survey on preparation techniques to identification of added medicinal plants, from determination of probiotic properties to estimation of important bioactive metabolites, from biochemical characterization to evaluation of antioxidant and antibacterial potentials, these locally sourced and endorsed beverages like *tongba*, *chhang*, *raksi*, *apong*, *yu*, *judima*, *zutho*, *opo*, *kiad* etc. have been subjected to research by scientists since past decade. This review work presented various documented aspects of Himalayan fermented beverages, their metabolite profiles and medicinal properties emphasizing high-altitude sickness healing potentials. Fermentation or preservation techniques are an integral part in the lives of indigenous populations lacking accessibility to mass produced goods, residing at the remote areas of high-altitude settlements. Different fermented foods and beverages of the Himalayas are exclusive to certain regions and curated to serve the well-being of these people under the unyielding conditions of montane life. It has allowed for the retention of this vast and unique repository of knowledge unknown to most. Due to the remoteness of these locations from large-scale markets, the indigenous populations rely heavily on locally produced and packaged beverages to tolerate the trials of a colder climate. Tourists also often indulge in these beverages to quench their thirst and benefits from their medicinal properties, which can help them to alleviate high-altitude sickness. Traditional products also hold cultural importance, often celebrated and sold during festivals (example: *guras* festival in Singalila ridge of Indo-Nepal and Sikkim). Therefore, these alcoholic beverages not only offer a refreshing experience but also provide economic opportunities through sales. However, it is noteworthy that the region lacks a large-scale production unit or industry dedicated to local alcoholic beverages. It is only confined to each ethnic group or community of the respective state, especially women who are associated with preparing these beverages. By embracing advanced food biotechnology or fermentation technology, the region can unlock the potential for large-scale production of these culturally

significant beverages. This initiative aims to satisfy the needs of both local residents and tourists while simultaneously fostering economic growth. As the world becomes more connected, these practices are becoming open for exploration by scientific research. The benefits are advertised to visitors and are catching the attention of scientists worldwide. Local tribes also emphasize sustainable practices, depending on cereals like *kodo* or finger-millet and ensuring the responsible harvesting of medicinal plants as they believe in maintaining a harmonious relationship with the natural world. The study of these cultural practices provided valuable insights into alternative healthcare approaches, promoting a balanced integration of traditional wisdom, spirituality, and sustainable living practices. Scientists claimed that medicinal activities of these beverages are associated to consumption, and they also alerted concerning effects of over-consumption of alcohol containing beverages. A significant concern of this venture may be the exploitation of and encroachment on long standing traditional customs. Since these beverages are strongly intertwined with the origin, habitat, religion, and overall way of life of tribes, they tend to consider these ethnic drinks as an integral part of their cultural heritage. Consequently, they strive to safeguard and preserve their traditional knowledge, shielding it from external influences and exposure. The documentation of the Himalayan ethnic fermented beverages has much demand at the present time, and there is a need to characterize the traditional products by studying their biochemical, microbiological, and the nutritive aspects, to provide scientific base for their present status and improvement by value addition. Current review may advise future in-depth studies such as in silico and in vivo experiments and pharmacology of ethnic beverages across the vast stretch of the Himalayan terrain targeting different high-altitude illnesses. Conducting rigorous scientific evaluations, including clinical trials and biochemical studies, could help validate the efficacy and safety of these traditional remedies and potentially lead to the development of new therapeutics for managing high-altitude sickness.

Abbreviations

HAS	High altitude sicknesses
AMS	Acute mountain sickness
HACE	High altitude cerebral edema
HAPE	High altitude pulmonary edema
DPPH	2,2-Diphenyl-1-picrylhydrazyl
ABTS	2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)
GC–MS	Gas chromatography- mass spectrometry
LC–MS	Liquid chromatography-mass spectrometry
HPLC–MS	High-performance liquid chromatography-mass spectrometry
LAB	Lactic acid bacteria

Supplementary Information

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Additional file 1.

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SM and MB conceived the idea and gathered online available literature from the internet. SM reviewed literature, performed meta-analysis and wrote the draft manuscript. MB revised the manuscript. Both authors read and approved the manuscript.

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